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The response of the near earth magnetotail to substorm activity

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Abstract

The large scale structure of the current sheet in the terrestrial magnetotail is often represented as the superposition of a constant northward-oriented magnetic field component (B_z) and a component along the Earth–Sun direction (B_x) that varies with distance from the center of the sheet (z_0 in GSM) as in a Hams neutral sheet. The latter implies that $B_x = B_{Lx} \tanh((z - z_0)/h)$ where B_{Lx} is the magnitude of the B_x component in the northern lobe. Correspondingly, the cross-tail current should be approximated by $J_y = (B_{Lx}/h)\,\mathrm{sech}^2((z - z_0)/h)$. Using data from the fluxgate magnetometer (FGM) on the Cluster II spacecraft tetrad, we have used measured fields and currents to ask if this model represents the large-scale properties of the system. During very quiet crossings of the plasmasheet, we find that the model gives a reasonable estimate of the trend of the average current and field distributions, but during disturbed intervals, the best fit fails to represent the data. If, however, the parameters z_0 and h of the model are taken as variable functions of time, the fits can be reasonably good. The temporal variation of the fit parameter h that characterizes the thickness of the current sheet can be interpreted in terms of thinning during the growth phase of a substorm and thickening following the expansion phase. Ground signatures that give insight into the local time of substorm onset can be used to interpret the response of the plasmasheet to substorm related changes of the global system. During a substorm, the field magnitude in the central plasmasheet fluctuates at the period of Pi2 pulsations.

Keywords: Magnetic storm; Substorm activity; Near earth magnetotail response

1. Introduction

In this brief report, we introduce an approach to the analysis of the temporal variation of the location and thickness of the magnetotail plasmasheet based on data from four Cluster spacecraft. The model is indubitably an oversimplified one, but the results are promising, allowing us to infer thickening and thinning of the plasmasheet at times consistent with complementary evidence of substorm expansion.

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2. The Harris neutral sheet model

The current structure in the magnetotail is often approximated by using the analytic expression referred to as the "Harris neutral sheet" that represents the component of the magnetic field along the Earth–Sun direction as

$$B_x = B_{Lx} \tanh((z - z_0)/h), \qquad (1)$$

where B_{Lx} is the magnitude of the x-component of the magnetic field in the northern lobe (Harris, 1962). Here, z_0 represents the position of the center of the current sheet and h is the scale of the plasmasheet thickness. Correspondingly, the cross-tail current density is

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$$J_y = (B_{Lx}/h)\,\mathrm{sech}^2((z - z_0)/h). \quad (2)$$

Field curvature is obtained by adding a constant northward-oriented magnetic field component (B_z) with no associated current. With Cluster, we measure both **B** and **J**, the latter being evaluated from the four spacecraft data intercalibrated using techniques described by Khurana et al. (1996, 1998). B_{Lx} can be approximated from lobe measurements made before the spacecraft enter the plasmasheet. We comment below on proposed methods for incorporating more realistic time dependence into the estimate of this parameter.

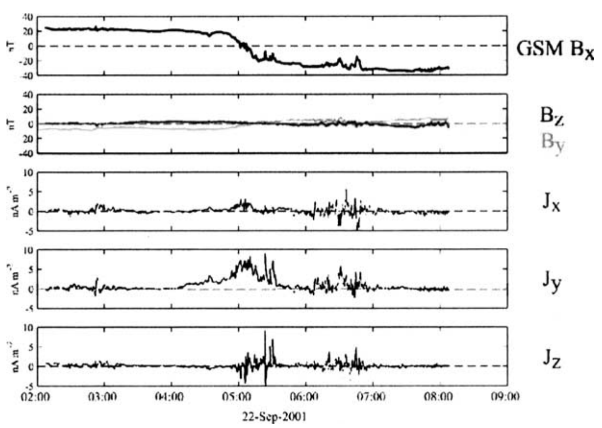

Fig. 1. (Upper two panels) Magnetic field components in nT measured by Cluster 1 for the current sheet crossing of September 22, 2001 (GSM coordinates). (Lower three panels) Current density in nA/m^2 obtained from magnetometer measurements on all four Cluster spacecraft.

3. Cluster plasmasheet crossings during quiet and disturbed intervals

During the interval July–October 2001, Cluster repeatedly crossed the tail plasmasheet near apogee (at radial distance near 19R_E) progressing from the dawn flank towards the dusk flank. Typical plasmasheet crossings lasted for ~6 h but the duration of the crossings ranged from 2 to 12 h. Although some crossings occurred during quiet geomagnetic conditions, the intervals of the plasmasheet encounters were commonly punctuated by substorm activity, and some passes were so disturbed that no stable current sheet model was applicable.

The early part of September 22, 2001 was unusually quiet with the AE index remaining below 100 nT until 0600 UT and below 200 nT until 0730 UT. Fig. 1 illustrates the magnetic field from the FGM magnetometer on Cluster 1 (Balogh et al., 1993, 1997) for the plasmasheet crossing. The cross-tail current density (J_y) rises to a maximum in the vicinity of the current sheet crossing where both B_x and B_y vanish. The change of sign of B_y at this time reflects the flaring of the magnetotail in the post midnight sector (with the field pointing slightly towards dusk in the northern hemisphere and towards dawn in the southern hemisphere). This feature (and the small increase of J_x in the center of the tail) would disappear in a skewed coordinate system slightly rotated around the z_GSM axis, but is not important for the purpose of this analysis.

Superimposed on the slowly varying structure of the current are short duration fluctuations that are present in all three components. Such fluctuations are particularly prominent from 0600 to 0700 UT when magnetic

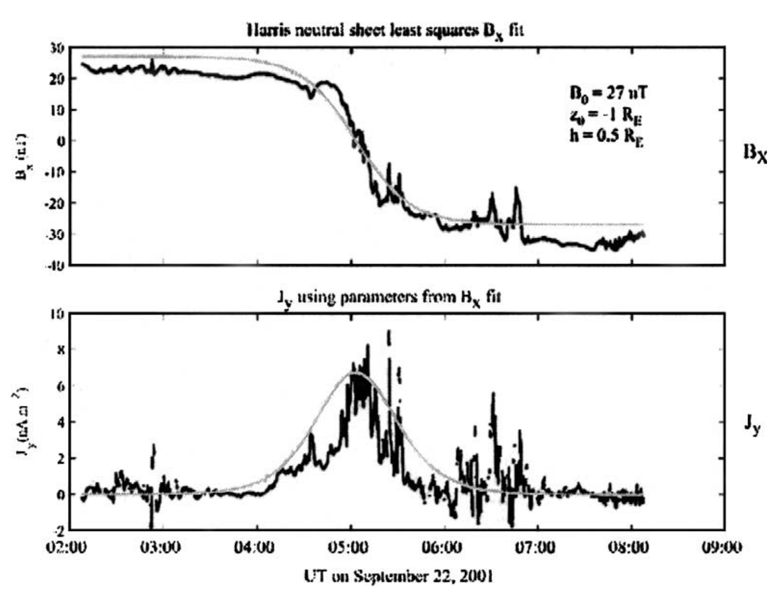

Fig. 2. (Upper panel) The measured B_x component of the field in the plasmasheet and a fit of the data to a static Harris neutral sheet model for the plasmasheet crossing of September 22, 2001. (Lower panel) The measured cross-tail current and the current inferred from the fit.

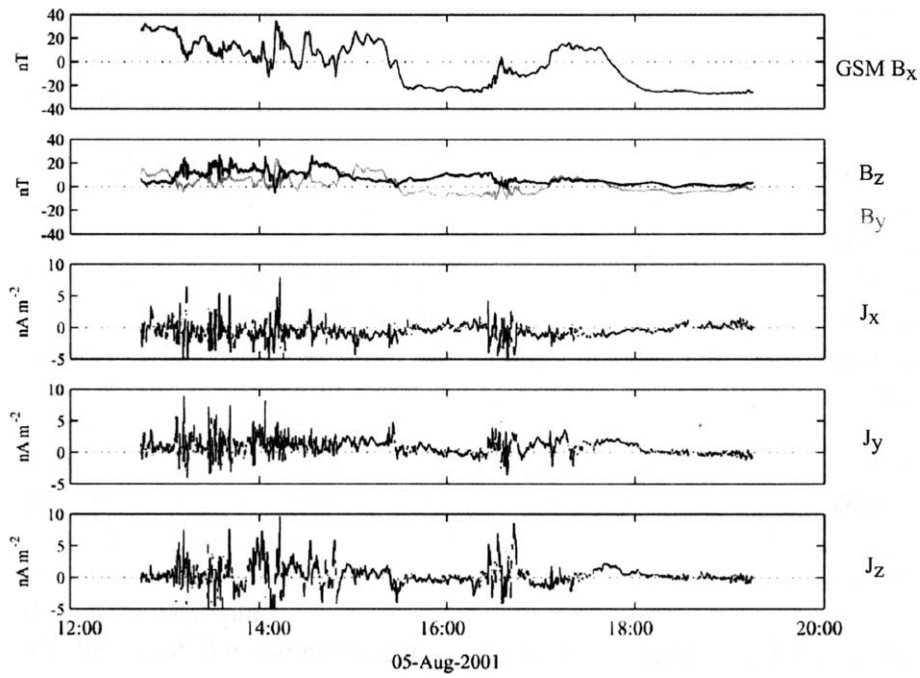

Fig. 3. As in Fig. 1, but for the plasmasheet crossing of August 5, 2001, a disturbed day.

activity begins to increase. In these high frequency fluctuations, the amplitudes differ little in the three components of the current density. Such current density fluctuations appear to develop in conjunction with substorm expansions as we illustrate below with another example.

Fig. 2 shows the fit of the x-component of the field on September 22, 2001 to the model functional form of Eq. (1) and uses the derived parameters in Eq. (2) which is found to give a qualitatively satisfactory fit to the measured y-component of the current density although its integral is too small to account for the reversal of the lobe magnetic field across the plasmasheet.

By contrast to the quiet day behavior of fields and currents, Fig. 3 shows the current sheet crossing of August 5, 2001, a disturbed day during which the AE index rose to >1500 nT at about 1430 UT. On this day, the current sheet flapped up and down over the spacecraft tetrad and the fluctuating small scale currents (of similar amplitude in all components) dominated the slowly varying currents over much of the pass, indicating that an MHD scale model is inapplicable.

4. Modeling time variability using both field and current measurements

A somewhat more satisfactory approach to fitting the currents in the plasmasheet recognizes that the three parameters of the model (the lobe field, the center position and the thickness) are variable. Two of the three varying parameters can be inferred by using the measured $B_x(t)$ and $J_y(t)$ as input parameters and inverting the Harris model (Eqs. (1) and (2)) to obtain Eq. (3) with $z(t)$ as the instantaneous spacecraft z-position

$$h(t) = \frac{B_L^2(t) - B_x^2(t)}{\mu_0 J_y(t) B_L(t)},$$

$$z_0(t) = z(t) - h(t)\tanh^{-1}\left(\frac{B_x(t)}{B_L(t)}\right). \tag{3}$$

Use of Eq. (3) imposes the requirement that the measured current be consistent with the observed lobe fields and thereby eliminates the inconsistency that we noted for the static model. In this initial analysis, we have not included the temporal variation of the lobe field but it can be inferred from $B(t)$ and the particle pressure $p(t)$ measured within the plasmasheet assuming north–south total pressure is constant in z. The latter effort will be undertaken in collaboration with the CIS particle detector measurements (Reme et al., 1997).

Using this technique on a set of crossings, we find that the plasmasheet thickness varies from 1 to $5R_E$ with smaller values found occasionally, often in conjunction with substorms. The current density is generally $<10\,\mathrm{nA/m^2}$. It is worth noting that McComas et al. (1986) estimated current density and sheet thickness from ISEE 1–2 magnetic field and plasma data and reported similar thickness but peak current densities ranging from $\sim$5 to $60\,\mathrm{nA/m^2}$. We have not observed such large current density, even during the exceptionally disturbed intervals of August 5, 2001 shown in Fig. 3.

5. Application to the substorms of August 15, 2001

As an application of the approach here described, we have considered the multiple substorms observed on August 15, 2001 and previously examined by McPherron et al. (2002). The plasmasheet crossing lasted for more than 12 h; Fig. 4 shows the magnetometer data from 0000 to 1600 UT. Throughout the first half of the day the IMF was weakly southward with a strong positive B_y. Three weak, multiple-onset substorms occurred as Cluster passed through the current sheet. Major onsets associated with these substorms occurred at 0143, 0431

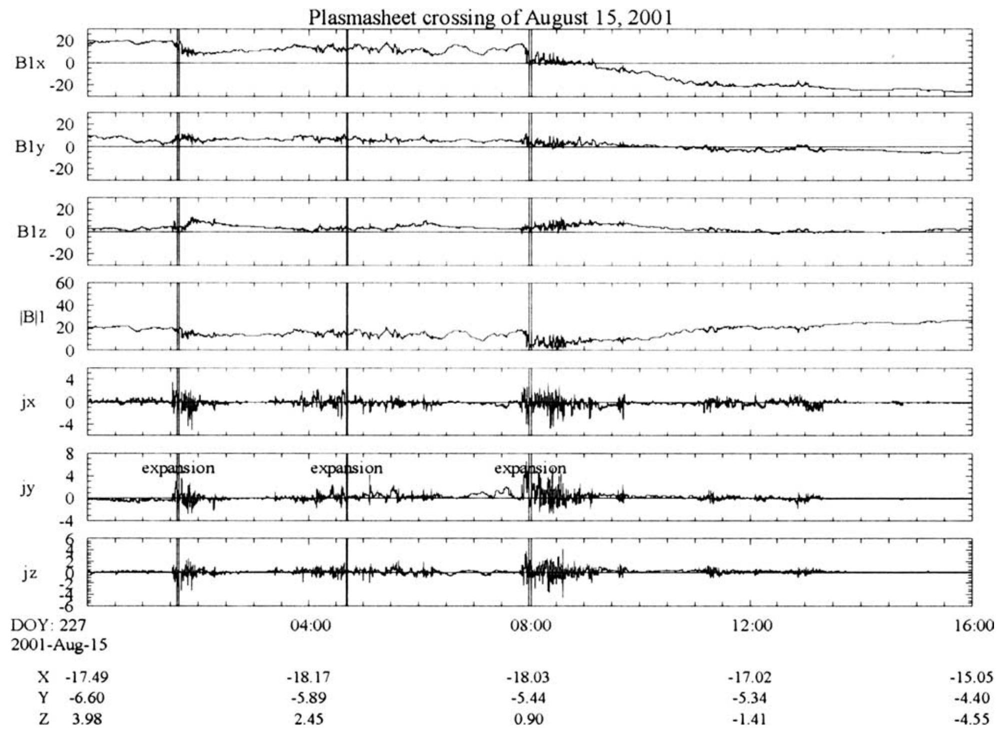

Fig. 4. Magnetic field (GSM components and the field magnitude) measured on Cluster land three components of the current derived from data of four Cluster spacecraft on August 15, 2001.

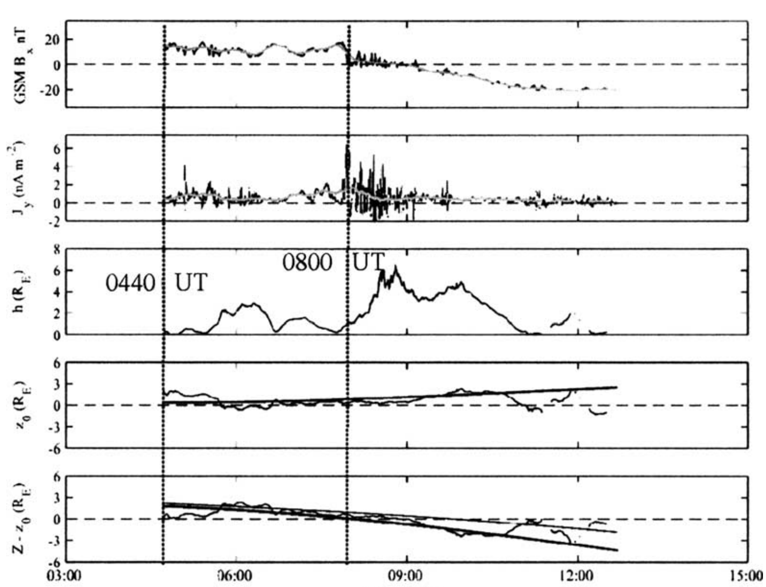

Fig. 5. From top to bottom, plotted vs. UT on August 15, 2001: 4 s averages of B_x at Cluster 1 for the current sheet crossing, 4 s averages and 10 min running averages shifted by one time step of J_y, the inferred scale thickness of the current sheet, $h(R_E)$, the location of the current sheet center, z_0 and the Hammond et al. (1994) prediction (thick line) which represents the trend quite well, and the distance in z between the spacecraft and the current sheet center again with the prediction. A vertical line marks the onset of the 0754 substorm.

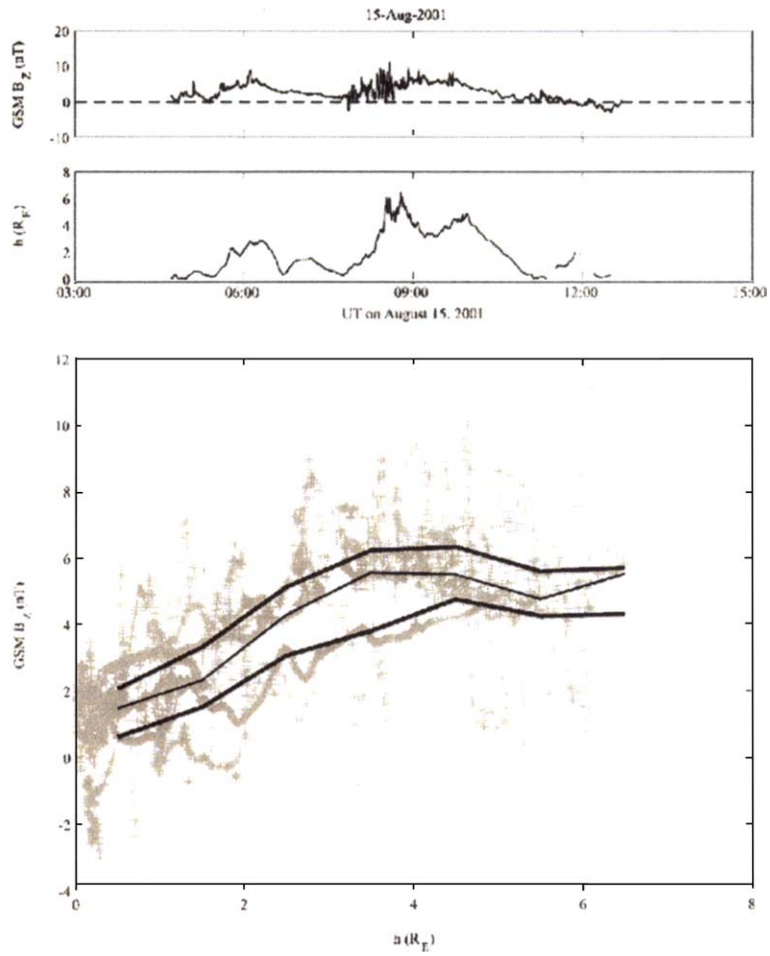

Fig. 6. For the substorm at 0800 on August 15, 2001, B_z (nT) at Cluster 1, $h(t)$ in R_E and the two parameters plotted against each other as points. Means and quartiles are plotted as lines.

and 0527, 0724 and 0754 UT. Most auroral activity in these substorms was localized well before midnight quite far from the meridian of Cluster. The preliminary AE index never exceeded 250 nT although stations not contributing to AE recorded disturbances as large as 500 nT. Roughly at each of these critical times, but particularly near 0800 UT, compressional and transverse fluctuations of the magnetic field increased in power as did fluctuations in all components of the current density.

In Fig. 5, B_x and J_y from Fig. 4 are shown with running averages used to determine the plasmasheet parameters $h(t)$ and $z_0(t)$, also shown in Fig. 5. A caveat to be noted is that parameters of the fit are not plotted when J_y is less than $\sim$0.2 nA/m^2 and that time variations of the lobe field have not been taken into account.

In the context of the near Earth neutral line model of the substorm one anticipates that at the location of the Cluster spacecraft, one should observe plasmasheet thickening accompanied by magnetic field dipolarization in the late expansion and recovery phases as the neutral line retreats down the tail (Baumjohann et al., 1992, 1999; McPherron et al., 1987; Sanny et al., 1994). In this context, it is interesting that the plasmasheet thickens somewhat after the 0440 UT substorm onset and more significantly at the time of the 0800 UT substorm onset. Fig. 6 shows that during the 0754 UT substorm, $h(t)$ and B_z in current sheet varied in phase.

The analysis presented here has been applied only to the data of a single pass through the plasmasheet but with two tail seasons already completed, we intend to test further whether systematic thickenings at substorm onsets can be inferred using the approach that we have adopted here from measurements at a group of spacecraft located within a time-varying plasmasheet. We believe that observations of this type may prove useful in mapping near earth magnetotail response as a function of local time position.

6. Periodicities of the field magnitude in the central plasmasheet

In the context of substorm investigations, we have also examined the characteristics of the fluctuations in the field magnitude, particularly in the central plasma-

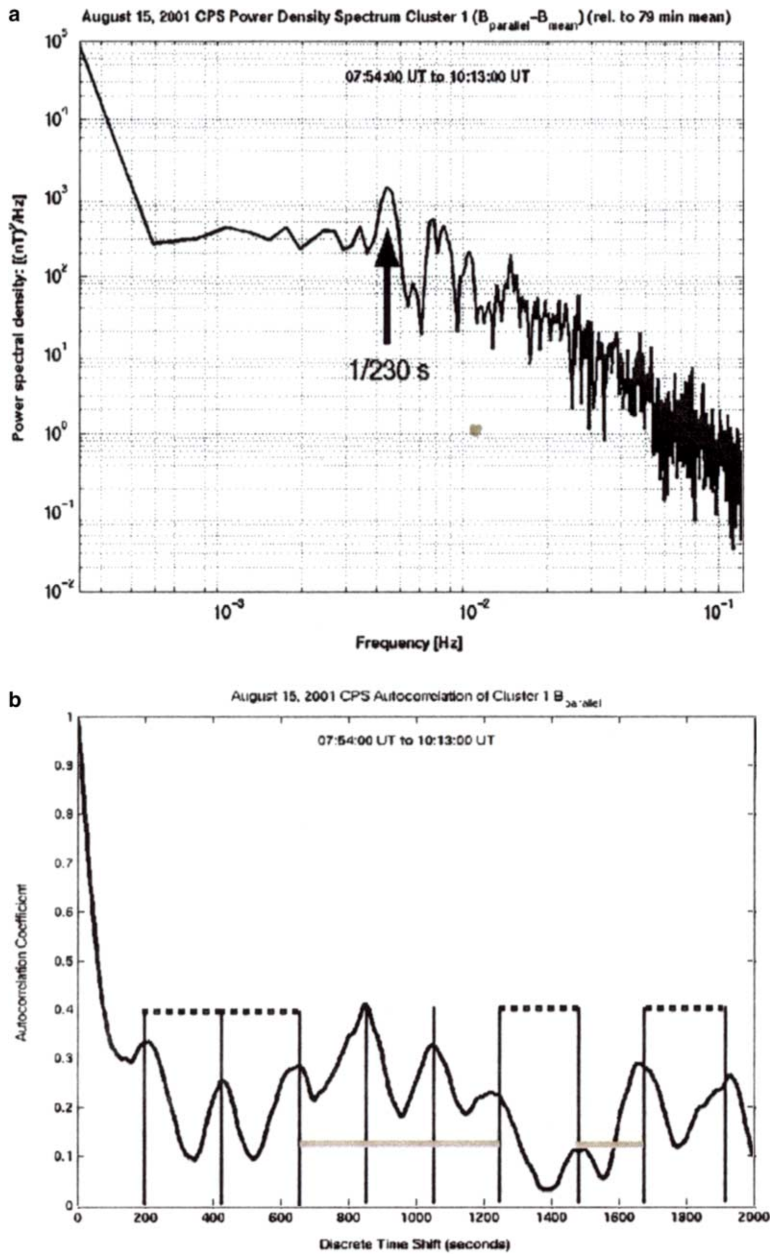

Fig. 7. (a) Power spectral density for the interval 0754–1013 UT in the central plasmasheet on August 15, 2001. (b) Autocorrelation function for the field magnitude in the central plasmasheet as in (a). Peaks joined by dotted (solid) lines are separated by ~230 s (~200 s).

sheet. Fig. 7 shows both the autocorrelation and the power spectral density of the field magnitude for an interval in the central plasmasheet. (For the FFT spectrum, a Hanning window was applied to segments of 1024 points with overlap of 512 points.) The autocorrelation function appears to oscillate with a period of ~230 s implying a peak in the spectrum at the corresponding frequency and indeed a spectral peak in the range 0.04–0.05 Hz corresponding to periods from 200 to 250 s is present. This band of frequencies lies in the Pi2 range, and the compressional nature of the perturbations appears consistent with generation by periodic bursts of high speed earthward flows of the sort identified by Kepko and Kivelson (1999) and Kepko et al. (2001) as the cause of Pi2 pulsations observed at low latitudes on earth. Transverse fluctuations in the centra: plasmasheet, although of similar amplitude, show no spectral peaks.

7. Summary

The cases studied to this time merely hint at the ways in which the data from the magnetotail seasons of the Cluster mission can enrich our understanding of the substorm process. Additional cases are being analyzed to establish how systematically the features herein discussed (thickening of the plasmasheet in conjunction with substorm onset and in particular coincident with local dipolarization, relatively narrow-banded Pi2 frequency compressional waves in the central plasmasheet) are present in the data. The local time dependence of the response in the magnetotail will add in a useful way to the types of investigations that we are pursuing.

Acknowledgments

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